STM Observations of Vortex Lattice Transitions in Mesoscopic Superconductors

Scientific Achievement

The behavior of materials at ever smaller length scales is a dominant theme in modern physical science. In mesoscopic materials, the free energy of the surface is comparable to or dominates the energy of the bulk, producing a rich variety of new equilibrium states which vary continuously with the surface to volume ratio. Superconducting nanostructures differ from bulk superconductors in another fundamental way. Vortices in bulk superconductors form a hexagonal lattice, while in mesoscopic structures they form various finite patterns that minimize the surface energy as well as their mutual repulsion. Recent theoretical calculations predict an orderly shell structure for the vortices, similar to the shell structure of electrons in atoms. Although the existence of such unique vortex states have been experimentally inferred from global magnetization measurements on simple mesoscopic structures, a direct image of the dynamics of confined vortex structures at the nanoscale has been elusive.

Here we show direct images of the vortex lattice configurations in a pre-fabricated mesoscopic single crystal superconductor using scanning tunneling microscopy. We observe co-existence of strongly interacting multiquanta vortex lattice and interstitial Abrikosov flux line lattice that form a composite magnetic field distribution undergoing transitions between different phase configuration states. The vortex configuration states are strongly dependent on the nanoscale architecture of the superconductor and applied magnetic field and temperature and point to the rich vortex phenomena to be explored at the nanoscale .

Significance

These studies elucidate the microscopic mechanism of topological vortex phase transitions in mesoscopic superconductors. Direct imaging of the co-existent lattices of multiquanta vortices and single quantum Abrikosov vortices highlights the complex nature of the interaction between the two magnetic sub-lattices that leads to enhanced current carrying characteristics of superconductors with nanoscale defect patterns. The work was published in *PRL **95** (2005) 167002* and was presented at the International Conference on Nanostructured Superconductors in Crete, Greece, Sept.2005.

Our success in fabrication of nanoscale single crystal superconductors (*APL **87** (2005) 242506*) brings us closer to the realization of other interesting mesoscopic systems. It lays the foundation for a new method to explore the vortex phase transitions in single crystal nanosize superconducting dots and triangles, and to directly image the elusive transition from an Abrikosov vortex state to a multiquanta Giant Vortex State.

Our newly derived synthesis technique can be applied to fabricate Hybrid ferromagnetic/superconducting heterostructures which are amenable for STM studies and which offer a plethora of new complex physical phenomena based on the interaction of superconducting vortices with an underlying spin domain structure. This unique capability would help us to understand the microscopic mechanism of the phenomena predicted in hybrid systems.

Performers

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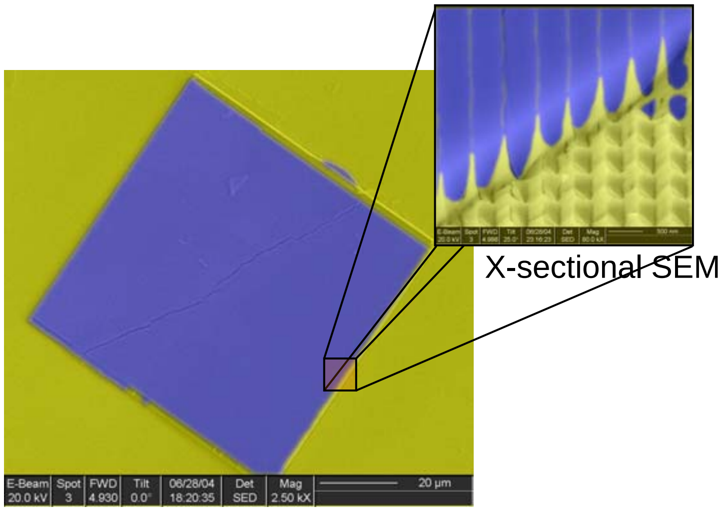
Novel FIB methods of preparing mesoscopic superconductors to be studied using STM



X-sectional SEM

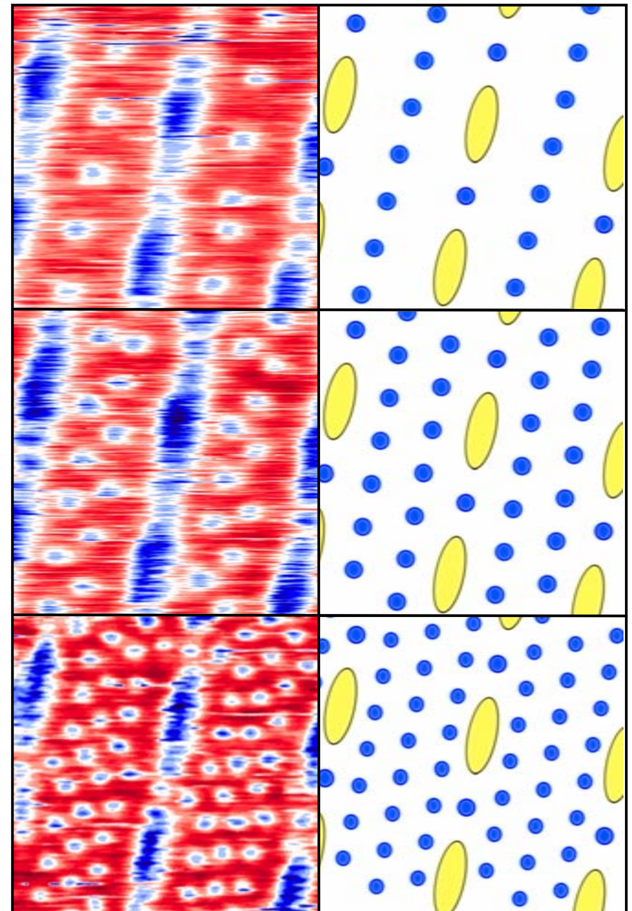
SEM image of $NbSe_2$ (blue) in gold (yellow) matrix

Geometrical Transitions to Multiple Vortex Chains

$H=10H_0$

$H=15H_0$

$H=26H_0$



1 chain

2 chains

3 chains

Accomplishments and future directions:

- Visualization of novel vortex phases in mesoscopic superconductors
- Developed enabling technique that opens the door to studies of mesoscopic materials using STM/STS;
- Spatial modulation of the sc order parameter due to proximity of normal materials (proximity effect) or spin and exchange fields

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